An Analysis of Oceanographic and Acoustic Fluctuations for Deep and Shallow Water Environments: Towards a Unification of Observations, Models, and Theory

John A. Colosi: PI
Department of Oceanography, Naval Postgraduate School, Monterey CA 93943
Phone: 831-656-3260 Fax: 831-656-2712 e-mail: jacolosi@nps.edu

Award Number: N00014-1-10313

LONG-TERM GOALS

The long-term goals of this research are to understand the predictability of acoustic variability in both deep and shallow water ocean environments.

OBJECTIVES

The objectives of this work are the development of accurate, and computationally efficient, reduced-physics acoustic propagation models for the prediction of the statistics of ocean acoustic signals. Three potentially useful models are being considered: 1) A coupled mode theory for acoustic propagation through random fields of sound speed perturbations, like those from the Garrett-Munk (GM) internal wave spectrum, or modification there-to for shallow water, 2) A coupled mode theory for acoustic propagation through shallow water, non-linear internal waves, and 3) Munk and Zachariasen (Rytov) theory for the prediction of spectra of phase and log-amplitude of low frequency, relatively short range propagation along a geometric ray path.

APPROACH

The approach to this work is to first test the aforementioned models using numerical experiments, to establish the regimes of validity (i.e. range, frequency, acoustic path, etc) with known, ocean sound speed fluctuation models. Once the acoustic scattering theory has been tested in this way, the models can be used to interpret data, where the environmental conditions have some degree of uncertainty. Experiments which will be used for model testing are, 1) the recent Long Range Acoustic Propagation Experiment (LOAPEX), and SPICE04 data, 2) the North Pacific Acoustic Laboratory (NPAL) data, 3) the Acoustic Thermometry of Ocean Climate (ATOC) data, 4) the South China Sea data, 5) the Shelfbreak PRIMER data, 6) the SLICE89 data, and 7) the SW06 data.

WORK COMPLETED

Work completed in the previous year has focused, by enlarge, on the numerical testing of the three aforementioned models. Regarding the coupled mode model for propagation through random sound speed fields, we have tested the model in deep water settings at a single frequency, and we have worked on the incorporation of broadband terms into the theory. The broadband model still needs to be validated by numerical experiment. The coupled mode model for shallow water, non-linear internal waves was formulated and tested by numerical experiment over the year, and we are ready to work on comparisons to observations. The Munk and Zachariasen model has had some numerical testing and has been compared to observations from the ATOC 87-km range, 75 Hz frequency Acoustic

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **An Analysis of Oceanographic and Acoustic Fluctuations for Deep and Shallow Water Environments: Towards a Unification of Observations, Models, and Theory**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Department of Oceanography,Monterey,CA,93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

engineering Test (AET). More extensive numerical testing of the Munk and Zachariasen model are underway right now, examining the regimes of applicability of the model as a function of frequency, range, and acoustic path.

RESULTS

A. Coupled Modes: Sound Transmission through Stochastic Ocean Internal Waves

Andrey Morozov (of Woods Hole Oceanographic Institution) and I have worked to develop a coupled mode theory to better understand acoustic intensity statistics. The approach is largely based on the work of Dozier and Tappert (1978), and of Van Kampen (1992), but our approach modifies their techniques enabling the computation of the important cross mode coherences. Broadband effects are also treated by computing the cross mode coherences across frequency. The primary mode coupling mechanism in the theory is a Bragg-like resonance between the difference modal wave-number and the internal wave wave-number. This work closely parallels efforts by Alex Veronovich and Frank Henyey. We also intend to extend the theory to deal with shallow water environments in which there is significant modal attenuation.

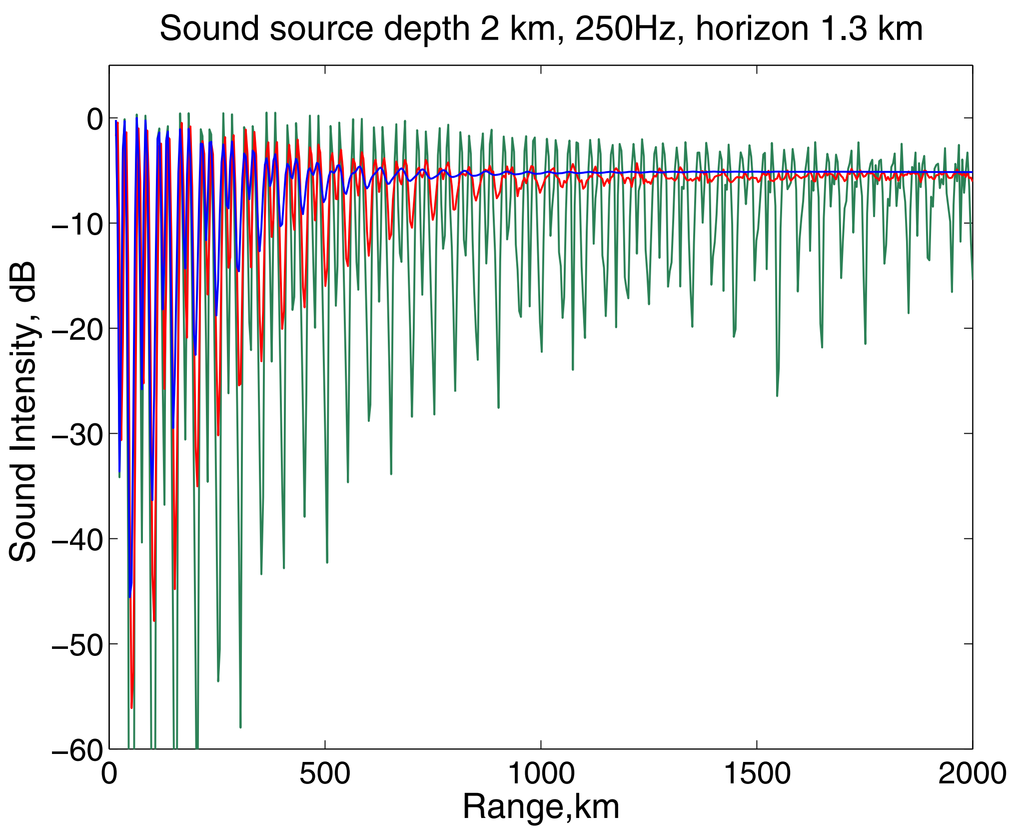

Figure 1: Monte Carlo Simulation (Red) and model prediction (Blue) of mean sound intensity for 250 Hz sound propagation through random fields of GM internal waves. In this example the source depth is 2-km, and the receiver depth is 1.3 km. The unperturbed sound intensity is plotted in green for reference. The model prediction is good to within a few dB, with biggest differences at low intensity. The unperturbed calculation for the mean intensity is clearly not appropriate.

Initial comparisons between our model and Monte Carlo parabolic equation simulations through Garrett-Munk internal waves at 250 and 100 Hz show the theory predicts the multi-megameter range evolution of the mean intensity to within a few dB. The theoretical calculation takes only a few minutes to compute while the Monte Carlo calculation takes several days. An example of the mean intensity computed from the theory and numerical simulation is shown in figure 1. The agreement between the model and the Monte Carlo simulations is excellent.

This year we have worked hard to include broadband effects into the model by computing cross modal coherences across different frequencies (Figure 1 only shows the single frequency result). The broadband theory has been worked out, but due to memory limitations on our present workstations, we have not been able to compute direct comparisons with the broadband Monte Carlo calculations. We expect to have new equipment soon to finish the calculation.

B. Coupled Modes: Shallow Water, Non-linear Internal Waves

Development of a model for shallow water propagation through non-linear internal waves has been very successful this year. Much of this work was done as part of the NPS masters thesis carried out by Lt Aaron Young (AUS). Using methods from quantum mechanical time-dependent perturbation theory, the following expression was obtained for the change in mode energy after acoustic propagation through a single internal solitary wave (ISW) of width Δ, position r_0, and maximum fractional sound speed μ_0,

$$|A_n(R)|^2 = |A_n(0)|^2 + 2\Delta\pi^{1/2}\mu_0 \sum_{m=1}^{N} A_m(0) A_n^*(0) C_{mn} \exp(-l_{mn}^2 \Delta^2 / 4) \sin(l_{mn} r_0)$$

where $|A_n(0)|^2$, $|A_n(R)|^2$ is the energy in mode n before/after propagation through the ISW, C_{mn} is a coupling matrix involving the acoustic mode functions m and n and the depth structure of the ISW, and l_{mn} is the beat wavenumber between modes m and n. The physical model here is of a Bragg type resonance between the ISW horizontal wavenumber component, that matches the beat wavenumber l_{mn}. It is important to note that although a perturbation theory approach was used here the model does conserved energy. Further, the model can also be used to predict mode energy changes through ISW packets or solibores, and it can be used to predict other acoustic observables like coherence or scintillation (more later). Figure 2 shows how the model predictions compare to parabolic equation simulations as the ISW width is changed from 20-m to 1000-m. The model is clearly better at lower frequency, but it is not completely inaccurate at the highest frequency tested (300-Hz). As expected, coupling is seen to be small for very narrow and very wide ISWs, and maximum coupling is obtained for an ISW width roughly equal to the beat wavenumber l_{mn}.

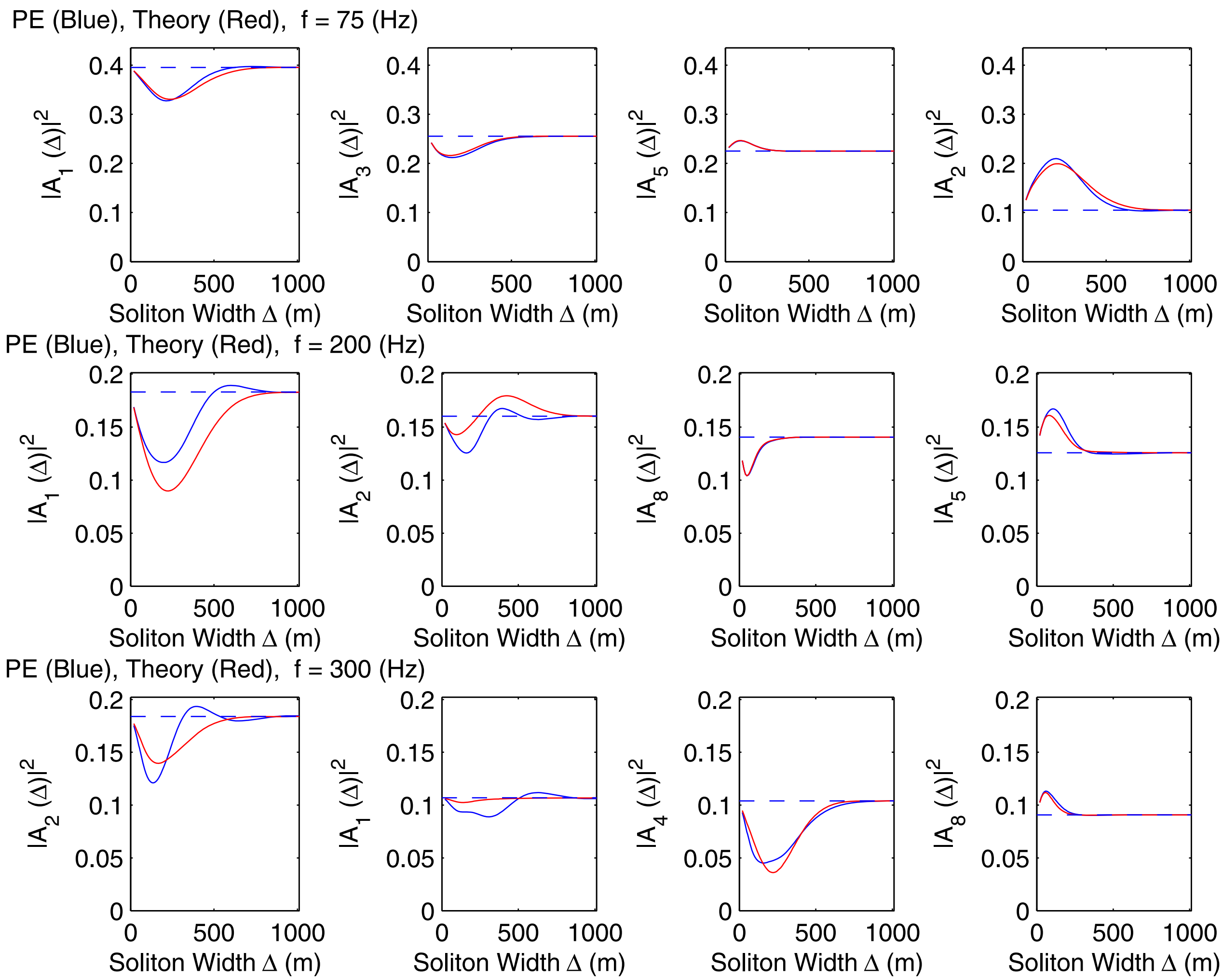

Figure 2: Parabolic equation (Blue) and model estimates (Red) of mode energies after propagation through an ISW with a maximum sound speed perturbation of 15 m/s for various ISW widths Δ from 20-1000 (m). The upper, middle, and lower rows are for acoustic frequencies of 75, 200, and 300 Hz. The straight dash curves show the initial mode energy at the source. The mode numbers chosen in the display are the four highest energy modes excited by the source.

Also of interest are the model predictions of mode energy as a function of ISW position r_0. Figure 3 shows the variation of mode energy for ISW positions between 1000 and 5000-m for the 150 Hz frequency, and an ISW width of 100-m. The agreement is seen to be excellent. Figure 2 (right panel) also shows results for the case of coupling through a packet of three ISWs of strength 15 m/s, 13.5 m/s, and 12 m/s; again the agreement is seen to be excellent. Note that the pattern of mode energy variation as a function of ISW position is not regular or repeating, but is modulated by the non-commensurate modal wavenumber difference l_{mn}.

Work is already underway to evaluate second order terms, which will improve the model at higher frequency. In addition the model is being adapted to predict other acoustical observables like coherence and scintillation.

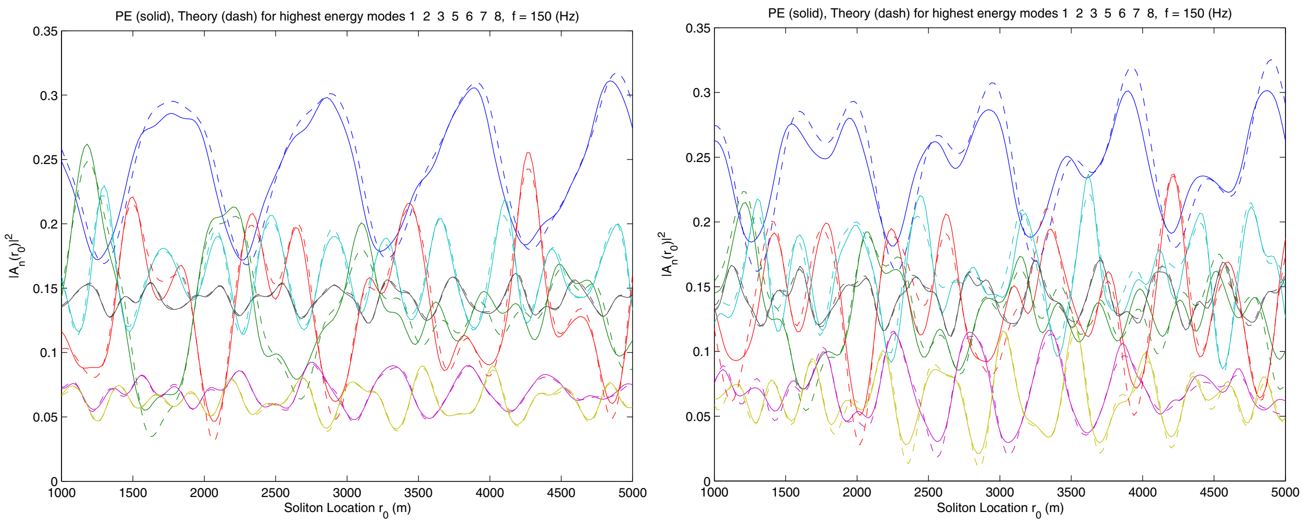

Figure 3: Parabolic equation simulations (solid) and model predictions (dash) of mode energies after propagation through ISW's of width 100-m, at a frequency of 150-Hz, for ISW positions from 1000-5000 m. The seven curves correspond to the seven most energetic modes. In the left panel a single ISW is modeled having a maximum sound speed perturbation of 15 m/s, while the right panel models a three ISW packet with maximum sound speed perturbations of 15, 13.5, and 12 m/s for each of the three ISWs. The agreement between model and numerical experiment is excellent.

The variation of mode energy as a function of ISW position in this 2-D model will have important consequences for situations in which the ISW propagation is at some small angle relative to the acoustic propagation path. In this case fully 3-d effects (i.e. horizontal refraction) are small, and the present model can be used in an Nx2D capacity. Two effects occur when there is a tilted ISW: First the effective distance, $r_{0,}$ to the ISW changes as a function of azimuthal launch angle from the source, and second the ISW appears to have a large width, Δ, as the mode intersects the ISW at a more glancing angle. Figure 4 shows just such a calculation for a tilted ISW. The striation pattern in the mode energy after propagation through the ISW is primarily caused by the variation of $r_{0,}$ along the ISW, and not the effective change in the ISW width. Work on this 3-d problem was part of an NPS masters thesis composed by Lt Doug Roush. Further numerical testing of this Nx2D application of the model will need to be carried out to establish what range of ISW angles, packet parameters, and acoustic frequencies in which out of-plane scattering is small.

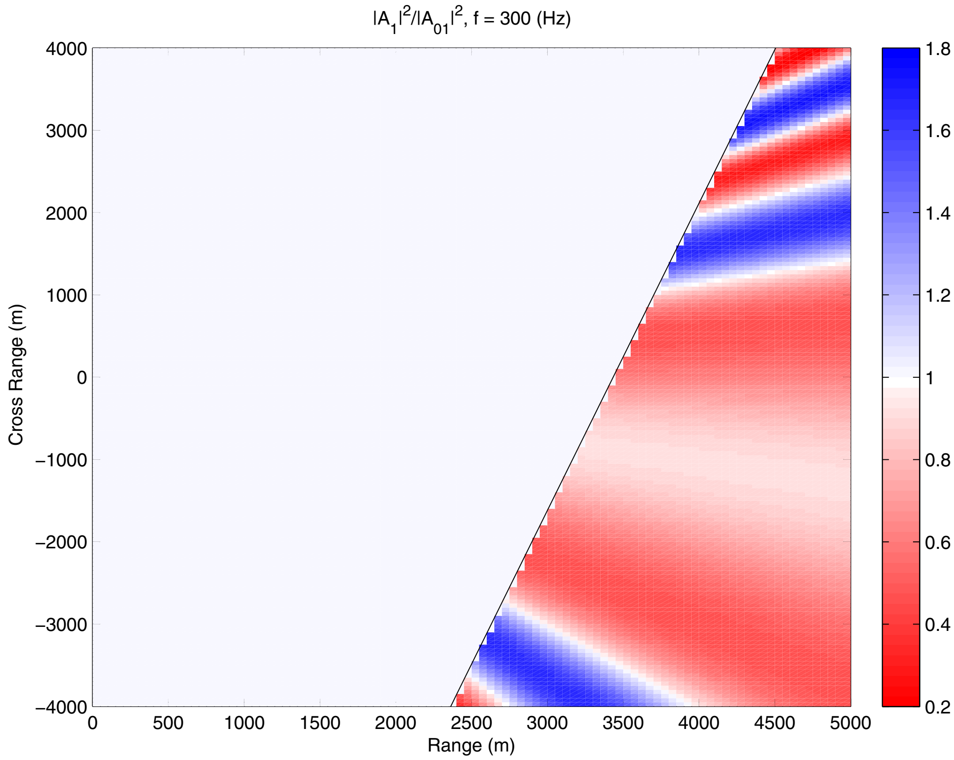

Figure 4: Model prediction for the ratio of unperturbed to perturbed mode 1 energy for 300-Hz acoustic propagation through a tilted solution (black line). The point source is located at the origin. The striation pattern past the ISW is due primarily to the variation of ISW position along the ISW front, rather than the apparent broadening of the ISW from the glancing angle.

C. Weak Fluctuation Theory

A PhD. student in the WHOI/MIT Joint program, Mr Jinshan Xu, and I are applying the weak fluctuation theory of Munk and Zachariasen (1976) to the prediction of frequency and vertical wavenumber spectra of phase and log-amplitude for acoustic propagation through random sound speed fields like those described by the GM spectrum. Here the spectra are written as integrals along a geometric acoustics ray path, and the acoustic fluctuations are only influenced by internal wave wavenumbers that are perpendicular to the ray path (assumed locally straight). Accordingly the frequency/wavenumber, (ω, k_z) spectrum of phase ϕ, and log-amplitude χ, at range R along ray path Γ is,

$$S_{\phi,\chi}(R,\omega,k_z) = \pi k_0^2 \int_{\Gamma} ds \Phi(k_\perp(\omega,k_z); z_{ray}) \left[1 \pm \cos\left(\frac{k_z^2 R_f^2(x_{ray})}{2\pi} \right) \right] H[\omega - \omega_L(z_{ray})] H[N(z_{ray}) - \omega]$$

where k_0 is a reference acoustical wavenumber, R_f^2 is the first vertical Fresnel zone, N is the buoyancy frequency profile, and Φ is the spectrum of internal waves evaluated at the perpendicular wave number given by

$$\Phi(k_\perp(\omega,k_z);z_{ray}) = \mu_0^2 \frac{N^3}{N_0^3}\frac{8}{\pi^3}\frac{k_{z*}}{k_z(k_z^2+k_{z*}^2)}\frac{Nf}{\omega^3}\left(\frac{\omega^2-f^2}{\omega^2-\omega_L^2(z_{ray})}\right)^{1/2}, \omega \geq \omega_L .$$

Note here that $\omega_L = (f^2+N^2(z_{ray})\tan^2(\theta_{ray}))^{1/2}$, (f is the local Coriolis parameter), is a low frequency cut off that depends on the ray angle; thus steep rays will not be able to interact with low frequency internal waves. Further there is a high frequency cut off at the local buoyancy frequency N, thus the spectrum has two Heavyside functions H to impose the low and high frequency cutoffs.

This analysis was motivated by the 1994 Acoustic Engineering Test (AET) data which demonstrated very weak acoustic fluctuations of 75 Hz sound transmissions to 87-km range. Figure 5 shows the comparison between Monte Carlo parabolic equation simulation through random fields of Garrett-Munk internal waves, and the theory for parameters close to that of the AET. The model is seen to closely predict the spectra even when a broadband signal is used (The Munk and Zachariasen theory assumes a narrowband). Presently an NPS master's student, Lt Serdar Tombul (TK) is working on extending the model comparisons to frequencies of 75, 150, and 300 Hz, 4 ray path geometries from axial to surface reflecting, and upto ranges of 200 km.

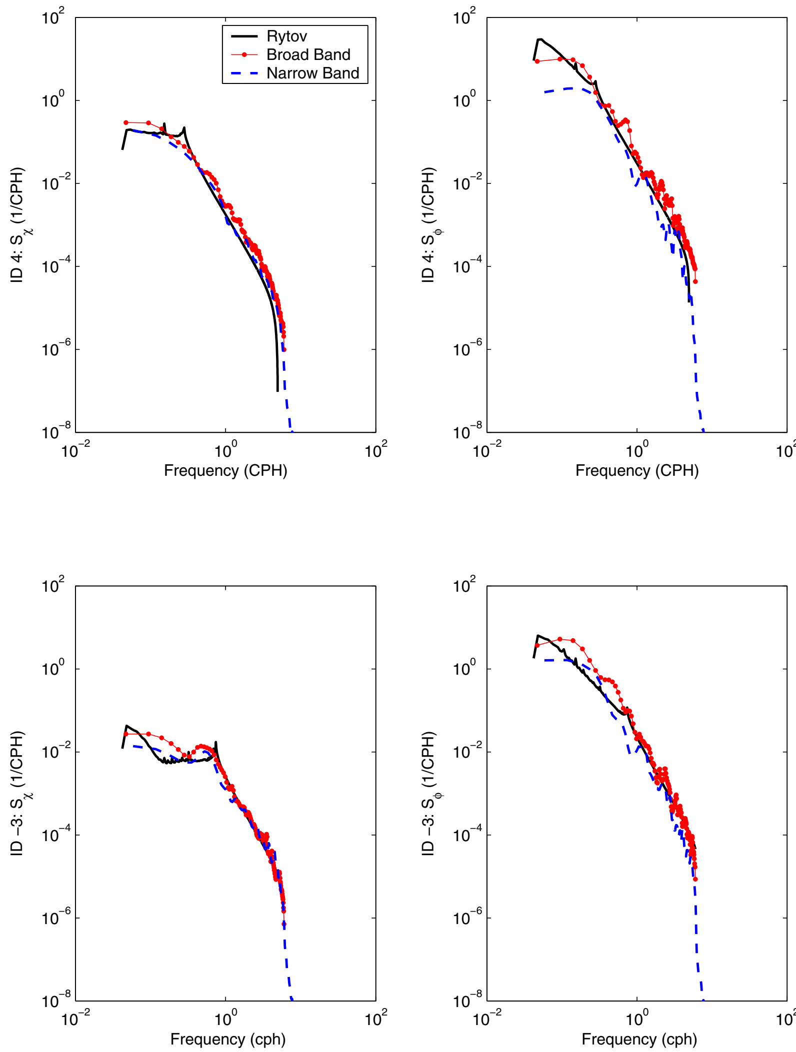

Figure 5: Frequency spectra of phase and log-amplitude from broadband (red dot), and narrowband (dash) parabolic equation simulations of sound transmission to 87-km range through random fields of Garrett-Munk internal waves. Black curves show the Munk and Zachariasen (Rytov) predictions. Two arrivals are modeled: one has a wavefront identifier of -3, and the other has a value of +4.

Next we compared the model to the log-amplitude frequency spectra from the AET. The comparison is limited to only relatively high and low frequencies because of the sparse time sampling of the AET, however Figure 6 shows that the agreement between model and observations is satisfactory. This comparison explains the rather curious observational result that the wavefront ID, -3, which traverses the sound channel at a higher angle has much less low frequency variability than the ID which has smaller angles and does not get as close to the surface. This attenuation of low frequency variability for steep rays is the consequence of the resonance condition between the local ray tilt and the internal waves with wave numbers perpendicular to this tilting ray. We believe that this result is the first observational evidence for this resonance condition.

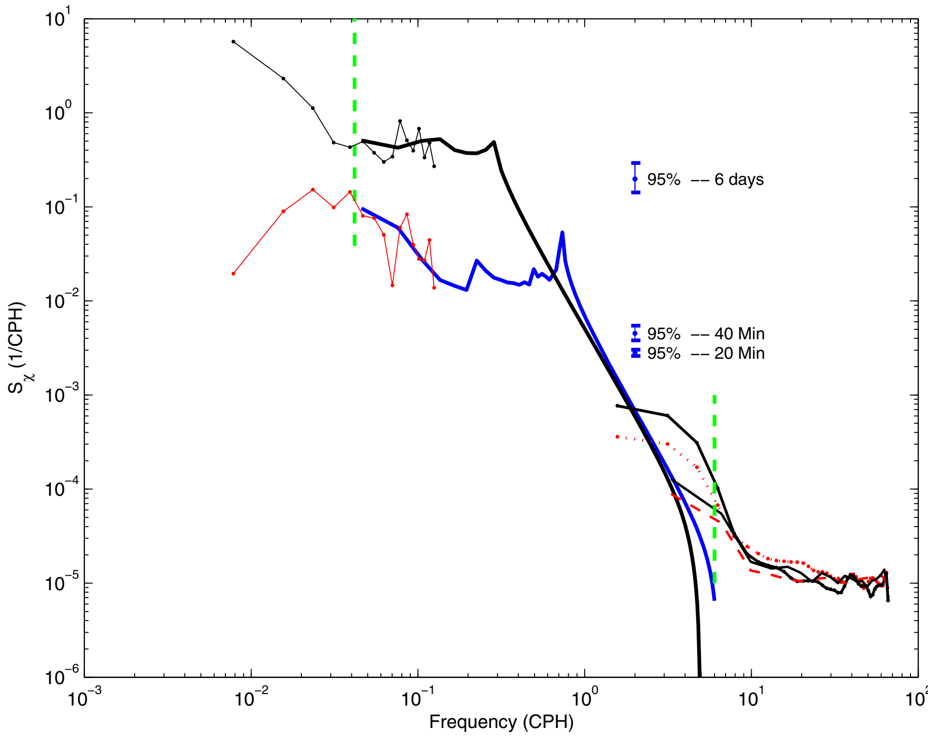

Figure 6: Observed and modeled frequency spectra of log-amplitude from the 87-km range, 75 Hz, AET. The observed spectra for wavefront ID's -3 (blue dots), and +4 (black dots) should be compared to the predictions, red for ID -3, and black for ID +4. The gap in the observed spectra is due to irregular sampling.

IMPACT/APPLICATIONS

There are several implications of this work to the understanding of acoustic predictability. A short list of the major issues/impacts are given below.

1) Our broadband approach to coupled mode theory for sound transmission through random fields of internal waves may provide the first theoretical framework to understand the in-filling of shadow zones from acoustic scattering. Examples include the vertical broadening of the wavefront finale, the vertical extension of wavefront branches observed at Navy SOSUS stations, and the energy scattering into the sound channel axial region from off-axis sources. The theory, so modified to include modal attenuation, may also have application in shallow water environments.

2) Progress on a coupled mode theory for low frequency long range propagation may be able to fill the gap in understanding left when the path integral theory of acoustic fluctuations was shown to be seriously flawed past propagation ranges of a few hundred kilometers.

3) Our 2-d coupled mode model for sound transmission through single or multiple ISWs is one of the rare examples of a reduced physics model for shallow water acoustic variability. The model may be applied to other acoustic observables besides mode energy, like coherence and scintillation. The model could also be used in a stochastic form given stochastic models for all the ISW

parameters like ISW width, phase speed, amplitude, and ISW number. Finally, as demonstrated here, the model can be used in an Nx2D mode to treat 3-D effects, and intensity striation patterns.

4) The Munk and Zachariasen theory will allow us to quantify the space-time scales of acoustic variability for low frequency, sound propagation over a few convergence zones. This information leads directly to models of coherence that can be exploited to construct ``optimal'' array and signal processing algorithms.

TRANSITIONS

None

RELATED PROJECTS

None

REFERENCES

1. Dozier, L.B. and F. Tappert, ``Statistics of normal model amplitudes in a random ocean: I. Theory'', J. Acoust. Soc. Am., 63, pp353-365 (1978).

2. Munk, W. and F. Zachariasen, `` Sound propagation through a fluctuating stratified ocean – Theory and observations'', J. Acoust. Soc. Am., 59, pp818-838 (1976).

3. Van Kampen, N. G., ``*Stochastic Processes in Physics and Chemistry*'', Elsevier Science, Amsterdam

RECENT PUBLICATIONS

1. Colosi, J. A. and A. B. Baggeroer, "On the kinematics of broadband multipath scintillation and the approach to saturation," J. Acoust. Soc. Am., V116(6), pp3515-3522, 2004.

2. Morozov, A. K. and J. A. Colosi, "Entropy and scintillation analysis of acoustical beam propagation through ocean internal waves," J. Acoust. Soc. Am.,V117(3), pp1611-1623, 2005.

3. Fredricks, A., J. A. Colosi, J.F. Lynch, G. Gawarkeiwicz, C.S. Chiu, and P. Abbot, "Analysis of multipath scintillations observed during the summer 1996 New England shelfbreak PRIMER study," J. Acoust. Soc., V117(3), pp 1038-1057, 2005.

4. Colosi, J. A., A. B. Baggeroer, B. D. Cornuelle, M. A. Dzieciuch, W. H. Munk, P. F. Worcester, B. D. Dushaw, B. M. Howe, J. A. Mercer, R. C. Spindel, T. G. Birdsall, K. Metzger, and A. M. G. Forbes, "Analysis of multipath acoustic field variability and coherence for the finale of broadband basin-scale transmissions in the North Pacific Ocean," J. Acoust. Soc. Am., V117(3), pp 1538-1564, 2005.

5. Baggeroer, A. B., E. Scheer, J. A. Colosi, B.D. Cornuelle, B.D. Dushaw, M. A. Dzieciuch, B.M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester, `` Statistics and

vertical directionality of low-frequency ambient noise at the North Pacific Acoustics Laboratory site'', J. Acoust. Soc. Am., V117(3), pp1643-1665, 2005.

6. Vera, M. D., K. Heaney, J. A. Colosi, B.D. Cornuelle, B.D. Dushaw, M. A. Dzieciuch, B.M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester, `` The effect of bottom interaction on transmissions from the North Pacific Acoustic Laboratory Kauai source, '', J. Acoust. Soc. Am., V117(3), pp1624-1634, 2005.

7. Voronovich, A.G., V.E. Ostashev, J. A. Colosi, B.D. Cornuelle, B.D. Dushaw, M. A. Dzieciuch, B.M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester, `` Horizontal refraction of acoustic signals retrieved from North Pacific Acoustic Laboratory billboard array data,'', J. Acoust. Soc. Am., V117(3), pp1527-1537, 2005.

8. Andrew, R. K., B. M. Howe, J. A. Mercer, J. A. Colosi, B.D. Cornuelle, B.D. Dushaw, M. A. Dzieciuch, B.M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester, `` Transverse horizontal spatial coherence of deep arrivals at megameter ranges,'' J. Acoust. Soc. Am., pp1511-1526, 2005.

9. Colosi, J. A. and W. Munk, "Tales of the venerable Honolulu tide gauge," *Journal of Physical Oceanography*, Vol. 36, No. 6, pages 967–996, 2006.

10. Lynch, J. F., J. A. Colosi, G. Gawarkiewicz, T. F. Duda, M. Badiey, B. Katznelson, J. E. Miller, and C.S. Chiu, "Inclusion of finescale coastal oceanography and 3-D acoustic effects into the ESME sound exposure model," IEEE J. Oceanic Eng., Special Issue on the Effects of Sound on the Marine Environment (ESME), V31(1), pp33-48, 2006.

11. Colosi, J. A., ``Geometric sound propagation through an inhomogeneous and moving ocean: Scattering by small scale internal wave currents'', J. Acoust. Soc. Am., V119(2), pp705-708, 2006.

PATENTS

None

HONORS/AWARDS/PRIZES

A. B. Wood Medal for "significant contributions to the understanding of acoustic scattering by internal waves in long-range propagation".